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The fluid flow consequences of CO_2 migration from 1000 to 600 metres upon passing the critical conditions of CO_2

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Abstract

The minimum injection depth for the storage of CO_2 is normally set at 800 metres. At and beyond this depth in the subsurface conditions exist where CO_2 is in a so-called critical state. The supercritical CO_2 has a viscosity comparable to that of a normal gas and a liquid-like density, Due to the high density of the supercritical CO_2, storing the CO_2 in the supercritical state is the most efficient geological storage The CO_2 will therefore be injected below the transition zone between subcritical and supercritical conditions. In the case of CO_2 storage in large aquifers, some part of the storage formation may lie at shallower depths where CO_2 occurs in gas phase. The CO_2 will also occur in the subcritical state (gas phase) in the case of an unintentional CO_2 leak from an existing storage site. In both cases it is crucial to understand how the CO_2 will behave when it reaches and passes this transition zone. In the case of intentional CO_2 injection in a shallow aquifer this knowledge is important to determine both the injection strategy and the available storage capacity of the aquifer; in the case of leakage, safety and risk assessment. In this paper we present the results of a reservoir simulation study, supported by a literature study, that considers the principles of CO_2 phase behaviour in the subsurface, and the implications for the injection strategy and storage volumes.

Carbon dioxide; Geological storage; Phase behaviour

1. Introduction

One of the early studies[1] to find the pros and cons of geological CO_2 sequestration concluded that the most efficient way to store CO_2 is in its most dense state, possibly solid state, but in terms of transport, the liquid state would be the realistic option. After comparing the prevailing pressure and temperature conditions of the subsurface with the phase behaviour of CO_2 it was concluded that CO_2 had to be stored below a depth of 800 metres (subsea, SS, in the case of an offshore storage site). At this depth the local pressures and temperature conditions are such that CO_2 will be in a so-called supercritical state, i.e. a highly compressed gas, with a gas-like viscosity and a liquid-like density. Through the years this 800 metre boundary has been the key condition for CO_2 storage. More recently, however, it was found that the absoluteness of such a boundary condition could jeopardise the storage operation. In some cases we are interested in what happens if the CO_2 migrates to places in the subsurface where the supercritical conditions are not present. In nearly all cases the density of the injected CO_2 will be less than that of the resident formation water, resulting in a tendency of the injected CO_2 to move upwards (buoyancy effect) until an overlying top seal acting as a flow barrier prevents its further movement. One of the obvious occasions where the transition zone between the supercritical conditions and the subritical conditions could be passed is in the case of a leakage from the containment due to either a seal failure or an induced leak. Another example where that could happen in the future is the Utsira storage site .Upper parts of this regional saline aquifer lie at depths less than 800 metres SS..

This paper investigates the fluid flow behaviour of the injected CO_2 during its transition from the supercritical state to the

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subcritical state and consists of three parts. The first part presents the results of a literature study on the consequences of the CO_2 state change on its pressure, volume and temperature (PVT) behaviour. In the second part, a three-dimensional multi-component reservoir simulator was used to model the behaviour of the injected CO_2. An existing reservoir simulation model of the Utsira Sand was modified in order to study the aforementioned transition phenomena. The third part discusses the impact of buoyancy and gas expansion of the migrating CO_2 on the geomechanical stability of the Utsira Sand intra-formational shales and caprock.

2. PVT properties of carbon dioxide

The depth which corresponds to the critical temperature and pressure depends on the composition of the CO_2 phase, the ionic strength of the brine and the local temperature profile (Fig. 1). The typical aquifer has a potential for supercritical fluid conditions beyond a depth of about 800 m under normal pressure and geothermal gradient.

The density of carbon dioxide as a function of pressure and temperature is displayed in the phase diagram in Figure 2 [3]. The critical point for pure CO_2 lies at 31 °C and at a pressure of 73.7 bar. During the change from supercritical to gaseous CO_2, at a depth of around 800 m, the viscosity increases slightly, while the density drops very abruptly from around 660 to 300 kg/m^3. In terms of storage efficiency, this means that under subcritical conditions, more than twice the amount of brine needs to be displaced/compressed in order to store the same amount of CO_2 compared to supercritical conditions.

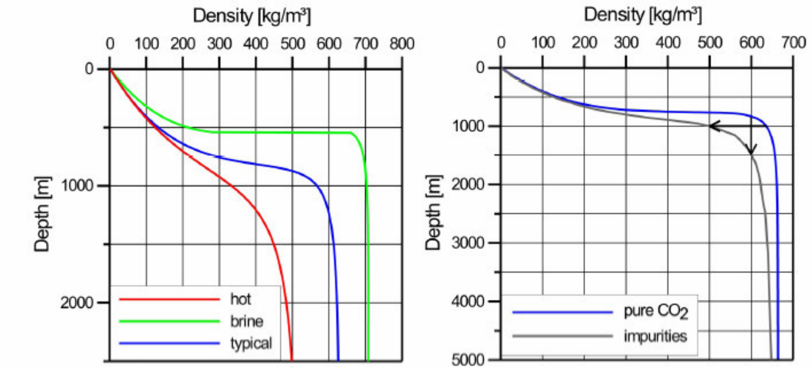

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Figure 1. CO_2 density variation with depth under the assumption of a): hydrostatic pressure and typical temperature gradients (blue); elevated geothermal gradients (45 °C/km; red) and high brine concentrations (green); b) Effect of impurities e.g. 2.75 % O2 and other components [2].

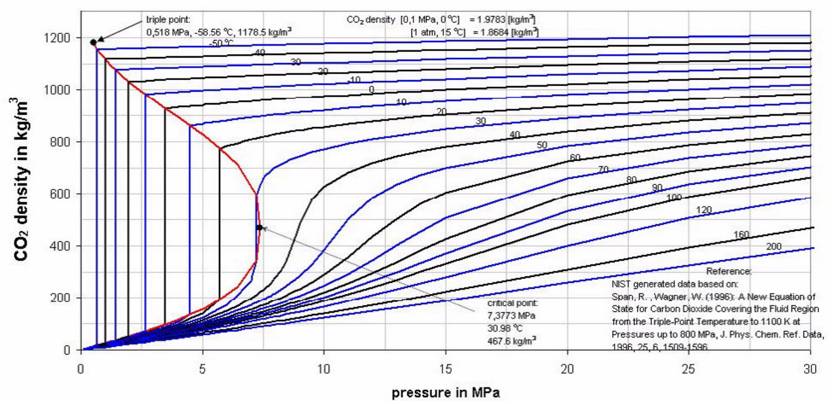


Figure 2. The PVT properties of CO_2.

2.1. Experiences with aquifer injection

The first industrial CO_2 injection in an aquifer started in October 1996 (www.statoilhydro.com) in the Utsira formation, off the coast of Norway. At Sleipner, the CO_2 is injected at a depth of about 1000 m. The top seal at this location is at a minimum depth of around 800 m. Other examples of aquifer injection sites are listed in Table 1.

Table 1. CO_2 injection locations.

Name	Country	Depth injection (m)	Comments
Carson	USA	Unknown	
Frio	USA	1700	
Mountaineer	USA	2700	
Sleipner	Norway	1000	
Ketzin	Germany	800	Injection about to start (mid 2008)
Snohvit	Norway	2500	Injection about to start (mid 2008)
In Salah	Algeria	1800	
Nagaoka	Japan	1100	Thin aquifer
Gorgon	Australia	2750	Thick aquifer
Otway Basin	Australia	2000	

Table 1 shows that the majority of CO_2 injections in deep saline aquifers is well below the threshold value of 800 m. This means that the injected CO_2 will remain supercritical throughout the upward migration and that abrupt changes in physical properties will not occur. The two sites where aquifer conditions approach the critical point of CO_2 are the Sleipner site and the proposed injection site at Ketzin. As conditions in both aquifers are close to the critical point, physical properties such as viscosity and density can be expected to show significant variation during the CO_2 ascent from the injection point to the top seal. The injection at Ketzin at a depth of 800 m depth and with the top seal of 600 m could provide very useful insights in the fluid flow behaviour close to the critical point. However, at the time of writing the actual injection at Ketzin had not yet started and no data on the migration and phase behaviour are available.

There are several field experiments that investigate natural geological accumulations of CO_2 in the subsurface. Examples of CO_2 accumulations in Europe are the Florina field in Greece , Latera in Italy [4], Mátraderecske in Hungary and Montmiral in France [5]. To the best of our knowledge, however, most of these studies are aimed at investigating emissions into the atmosphere, monitoring techniques, etc. and not CO_2 migration in the subsurface. The findings of these experiments are therefore of less interest to the current study, with the exception of conclusions that in all these instances the CO_2 emissions occur in a controlled manner without any form of sudden or explosive gas release.

The overall fate and migration of the CO_2 at the Sleipner location have been studied in great detail. Arts et al. [6] for example, provide an overview of the seismic monitoring conducted between 1994 (before the start of the injection) and 2006. An important observation was that the injection process at Sleipner, at least until 2001, did not reveal any significant increase in pressures. That was attributed to the very high permeability of the aquifer, which allows for the rapid redistribution of fluids and dissipation of increased pressures [7].

2.2. Implications for current study

The permeabilities in the Utsira aquifer are very high and the respective density and the viscosity of the CO_2 supercritical phase are significantly lower and higher than of the ambient brine. Although this would indicate a possibly rapid ascend towards the seal, the migration rates are still expected to be low enough so that the change in properties of the ascending CO_2 with respect to time is rather gradual. This means that the rate of expansion is relatively low compared to the advection rate of the brine. The local increase in the pore pressures can therefore be expected to be low. After the CO_2 has become subcritical, the density especially will decrease significantly while the viscosity will decrease only slightly. This indicates that the upward migration after the critical point will even accelerate. Local increase in the pore pressures can therefore be expected to be low. The reservoir simulation as described in the following section will confirm that.

Based on physical principles described above a few recommendations for the injection strategy can be drawn. From Fig 2, it can be seen that the density drops by more than half after the CO_2 reaches subcritical conditions. This means that the storage capacity in the aquifer for traps under subcritical conditions is also lowered by more than half. In our view, it is important to store CO_2 as much as possible under supercritical conditions (deeper then 800 m). One way to store at least part of the carbon dioxide is to select an area of the Utsira formation with favourable configurations of the top seal, which will retain part of the CO_2 at greater depths. The intra-reservoir shales, as mentioned by Chadwick et al. [2], could also act as a barrier to upwards CO_2 migration. If these shales have high entry pressure that is not overcome exceeded by the injected CO_2, the CO_2 will remain below the shale. On the other hand, if the permeability of the storage formation is low, the CO_2 flow will be slow and the reservoir pressure will increase in time.

3. Reservoir Engineering Aspects

3.1. Introduction

The Utsira Sand is a shallow, extensive saline aquifer under the central and northern North Sea. The Miocene - Early Pliocene Utsira Sand is poorly consolidated, has a high porosity and permeability of 1-5 Darcies and is approximately 200-300 m thick. Well data (wire line-logs) and seismic data indicate the presence of interbedded shale layers in the sand (sub-horizontal and discontinuous) that form baffles and local barriers to vertical flow. The Utsira Sand is located at a depth of about 900m below sea level, in water depths of about 80 m. The Utsira Sand underlies an area of over 26,000 km2 and has an estimated pore volume of 55 x 10^{11} m^3, making it suitable for CO_2 storage. The top of the Utsira Sand is marked by a 10 metre thick shale layer which lies at a depth of close to 800 m to the south part and 600 m to the north.

3.2. Modelling and Reservoir Simulation

The reservoir simulator was used for modelling the upward migration of CO_2. The key assumption in the modelling was that buoyancy is the driving force of upward migration and that structural dip and the presence of barriers and baffles are the secondary controls of the migration pattern. Impermeable to poorly permeable intra-reservoir shale layers impede or slow down vertical migration and cause the CO_2 to accumulate in lenses underneath these layers. Some shale layers are semi-permeable, and/or have local spill points, which controls the locations where further migration of CO_2 to the overlying layers can take place.

In the three-dimensional, multi-component reservoir simulator used in this study the gas phase density is calculated by the Peng-Robinson Equation of State (PREOS) with a Chien-Monroy correction, and the viscosity is calculated using the Jossi-Thiel-Thodos method. TNO has further improved the modelling capability of this code by implementing a temperature gradient possibility that is mainly driven by high sensitivity of the CO_2 density to temperature. The model is, in principle, isothermal and there is no calculation of heat transport or exchange. However, initialising each grid block at its initial temperature enables the PREOS to calculate the temperature and pressure-dependent CO_2 densities at the relevant depths, with the assumption made by TNO that the heat capacity of the subsurface is high enough to heat up the injected fluid instantaneously.

3.3. The Simulation Model

We modified an existing Utsira model to be used in this simulation study, the total dimensions of which are 46 x 62 x 60 grid blocks. In the central part of the model the majority of the grid blocks each represents an area of 50 by 50 metres with a minimum thicknesses of 1 metre. In order to cover the largesr possible reservoir (affected volume), the maximum grid sizes at the model boundaries are up to 6,000 metres. In total the resulting model covers an area of 23.3 by 25.4 km. The model has a uniform porosity of 30 per cent with a net to gross ratio of 1. Furthermore, we assumed the sand to have a uniform horizontal permeability of 3,500 mD. The aerial extents and the sealing capacity of individual shale layers interbedded in the aquifer sand body are the main controls of the shapes and sizes of the CO_2 lenses and migration paths. Some of these shale layers may have vertical permeability of less than 1 mD.

Three simulation models were developed. The base case run was made on a model with the original depth level of the Utsira Sand, some 800 metres at its shallowest point. By lifting the whole model up by 200 metres we created the second model with a minimum depth of around 600 m SS.. The third, worst-case scenario model was developed by using the uplifted reservoir model and excluding intra-reservoir shale layers from the aquifer formation. For all runs the same CO_2 injection strategy has been used: one 7” injector with a daily injection rate of 1,380,000 Nm3/d. The total injection period was 10 years followed by a 10-year shut-in period.

3.4. Simulation Results

Simulation results yielded the following insights which are valid for all cases.As soon as the CO_2 is injected into the lower part of the aquifer it starts to migrate upwards. When the CO_2 arrives at an impermeable shale layer, it starts to accumulate and/or migrate laterally. However, if a leak path or a spill point is encountered, upward migration resumes. In the case of the Utsira formation, the CO_2 pressure underneath the baffle (intra-reservoir shale layer) keeps building up due to the very low transmissibility and will eventually conduct CO_2. The CO_2 that escapes from the shale layer will migrate upwards and be stopped by the following barrier. This process is repeated until the CO_2 reaches the base of the sealing cap rock. Hence, it will be clear that for the case without shale layers the only barrier to upward CO_2 migration is the top seal.

Activating the thermal gradient functionality of the simulator has a significant effect on the effective density of the CO_2 when the temperature and pressures are very close to the critical conditions. For all runs the proper field temperatures are calculated assuming a fixed reference temperature of 37 °C at 1,050 m and a thermal gradient of 0.033 °C/m. Figure 1 shows that the density, and hence the volumetric behaviour of CO_2, is very sensitive to temperature. It is therefore probably misleading to make use of a reservoir simulator based on an isothermal formulation when simulating CO_2 injection in the lower part of a relatively thick storage reservoir,.

In the case of a set of sensitivity simulation runs in rather different conditions it is difficult to visualise all the effects and differences between the individual runs. For the sake of simplicity, we will show the areal extent of CO_2 accumulation at the top of the aquifer formation at 10 and 20 years after the start of injection.

Figure 3 shows the results of the base case simulation: CO_2 saturation distributions underneath the top intra-reservoir shale layer after 10 and 20 years marking respectively, the end of the injection period and the end of the 10-year shut-in period. In the base case a large amount of CO_2 is still trapped by one of the 7 individual intra-reservoir shale layers. Aquifer top in the base case model is at depths beyond 800 m and all CO_2 is still in supercritical condition.

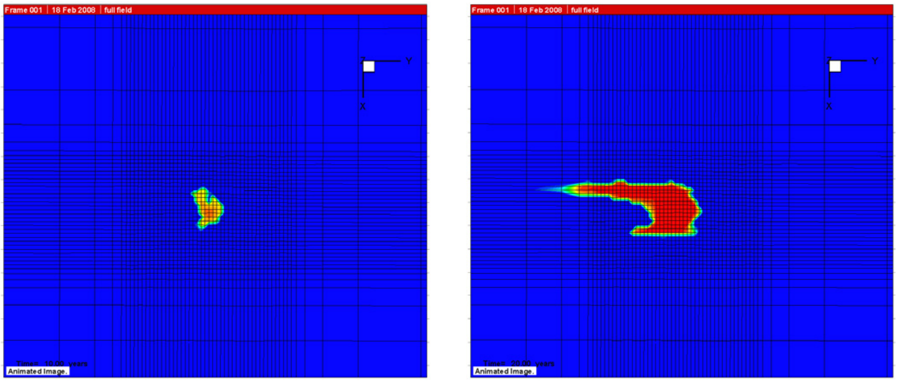


Figure 3. CO_2 distribution at top of the Utsira Sand after 10 and 20 years from the base case model - aquifer top at 800m depth (only central part of simulation grid shown).

Figure 4 shows the results obtained from the elevated model with the aquifer top at about 600m depth. When CO_2 passes a depth where critical conditions change to subcritical conditions, the CO_2 will become less dense resulting in a larger volume and density difference between the CO_2 and the brine. As a result, the velocity of CO_2 migrating upwards will increase (gravity segregation). From Figure 1 it is also clear that this change is much more drastic if transition happens at low temperature. At elevated geothermal gradients this transition is much more gradual. Some caution should be taken when interpreting the results in the left part of the contour maps where numerical dispersion takes place, mainly as a result of increasing grid size.

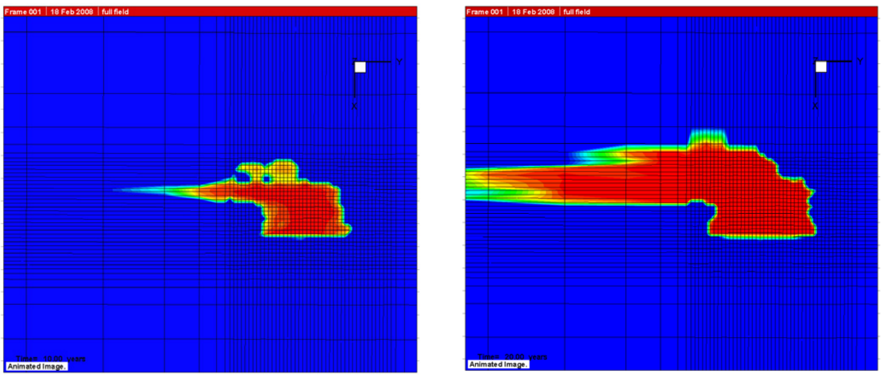


Figure 4. CO_2 distribution at top of the Utsira Sand after 10 and 20 years from the model with aquifer top at 600m depth (only central part of simulation grid shown).

Figure 5 shows the results obtained from the elevated model without intra-reservoir shale layers in the aquifer formation. The CO_2 will now percolate rapidly towards the top of the Utsira formation, where it will spread laterally. After 10 years of injection nearly all CO_2 will have arrived at the top of the formation. The difference between the 10 and 20 years is largely due to the effects of continuous dissolution of CO_2 into the formation water during the 10-year shut-in period.

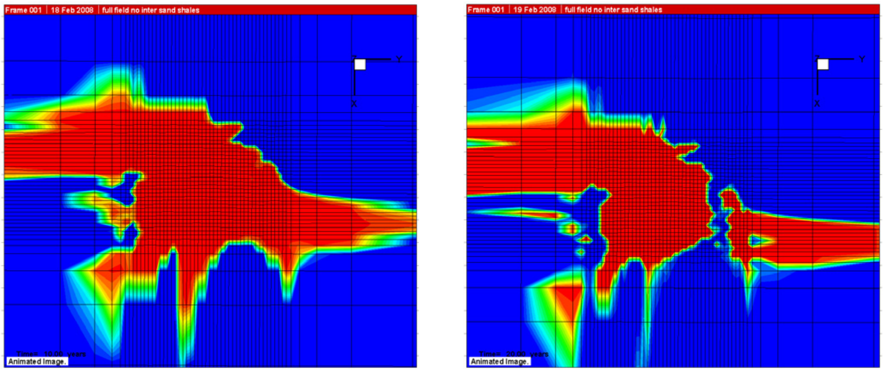


Figure 5. CO_2 distribution at top of the Utsira Sand after 10 and 20 years from the model with aquifer top at 600 m depth and aquifer without intra-formational shale layers (only central part of simulation grid shown).

4. Geomechanical Implications

The following processes and mechanisms could potentially affect the mechanical integrity of the intra-formational shales and the caprock , trapping the CO_2 bubble or the storage formation:

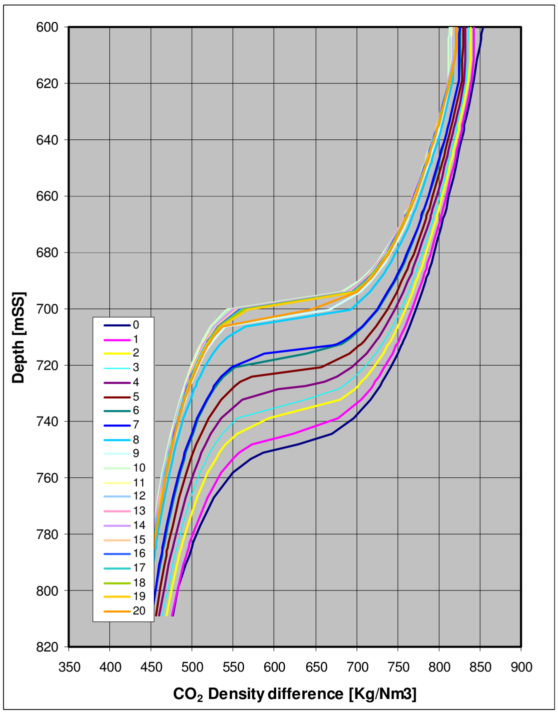
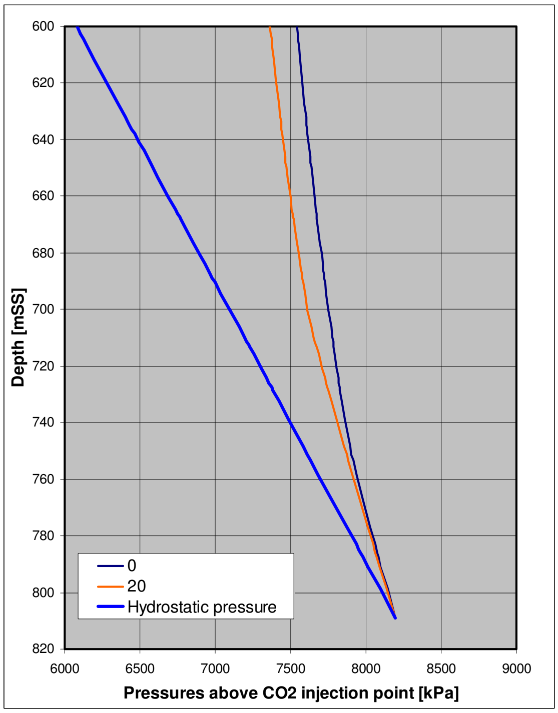


Figure 6. Density difference between brine and CO_2 above the injection point for different times (in years) after the start of injection



.Figure 7. Pressure profiles above the injection point (810 mSS) up to the aquifer/caprock interface (600 mSS) for different times (in years) after the start of injection. The initial pressure is hydrostatic

1) Pressure increase due to CO_2 injection.

The total absolute increase in average reservoir pressure amounts to 400 kPa (4 bars), based on reservoir simulations. Such a small pressure increase in the targeted aquifer causes a minor change in the effective stresses. The resulting mechanical effects are minor and it is very unlikely that the mechanical stability of the sand or the shales will be affected.

2) Buoyancy effect due to different densities of the injected CO_2 and formation water.

A lower density of the supercritical CO_2 with regard to the brine, and the substantial decrease in density when CO_2 goes from the supercritical to the gaseous phase, will increase the buoyancy effect. We have estimated the overpresssure caused by the buoyancy effect for the very unlikely worst case of a CO_2 column with a maximum height of 200 m, assuming that the intra-formational shale layers are not present in the storage sand formation. For the density differences shown in Figure 6, we estimate that the overpressure on the caprock of the Usira sand will amount to 1,280-1,460 kPa (Fig 7). A significant decrease in CO_2 density at phase change, at depths of 700-750 m, causes a faster build up of overpressure above these depths (Fig 7).

The sealing capacity of the caprock was estimated by measuring the capillary entry pressure on a core material taken from the Nordland shale (caprock) at the Sleipner site (Arts et al. [2]; Harrington et al [8]). The measured capillary entry pressure was 3,300-3,500 kPa for both nitrogen and gaseous CO_2, and about 1,700 kPa for supercritical CO_2. If we assume that the caprock of the storage formation is homogeneous, and that these experimental values apply to the whole caprock, then it follows that the gaseous CO_2 capilary entry pressure in the caprock is more than two times higher than the overpressure at the aquifer/caprock. In other words, 37-42% of the sealing capacity of the caprock is sufficient to prevent penetration of the gaseous CO_2 into it. In the case of supercritical CO_2 at the aquifer/caprock interface, the capillary entry pressure to supercritical CO_2 is about 1.2-1.3 times greater then the overpressure generated by the CO_2 buoyancy effect. In this case 75-86% of the caprock sealing capacity has to be mobilised to prevent CO_2 penetration into it. According to this preliminary estimate for the very unlikely worst case, CO_2 is not expected to penetrate into the caprock assuming that there are no faults or fractures, etc.. Seismic monitoring of the Sleipner site has shown that the thickness of CO_2 accumulations underneath the intra-formational shale layers is in the order of 10 m, which is much less than the total thickenss of the aquifer (~200m) considered in the described worst case.

3) Washing out of fine particles (suffusion) from the Utsira Sand by the stream of injected and mobile CO_2 at phase change from supercritical to gaseous phase.

Phase change of supercritical CO_2 to gas at depths from 700-750 m is accompanied by the simultaneous gas expansion and substantial decrease in CO_2 density. At phase change the CO_2 fluxes/velocities will increase significantly. The fluxes were not available from reservoir simulations to be able to quantify them. However, a very high permeability of the Utsira aquifer in all directions, its enormous size (26,000 km^2) and the range of depths (700-750 m) where the phase change is expected to take place, make the possible effects of suffusion, if it at all takes place, very localised and unlikely to affect the transport properties of sand.

Conclusions

The results of the simulation work in this study have been based on a non-validated numerical model. Hence, the numerical simulation model used was developed using common state-of-the-art principles, formulations and assumptions of complex physical processes. Furthermore, the model is based for a large part on publicly available data from the Norwegian offshore territory.

We can use the Figures 8 and 9 to explain the general outcome of this study. Figure 8 represents the pressure profile for a vertical column of gridblocks located directly above the injection point to the seabed. The different profiles mark the development of the pressure profile through the simulated time on a yearly basis. From this plot two clear conclusions can be made. The almost straight line character of the profiles is the result of the very high permeability (conductivity) of the Utsira Sand in all directions. Any local pressure increase is directly distributed over the whole formation. Furthermore, the nearly parallel pressure increase is the result of the volumetric effect of fluid injection in a closed system. Consequently, if a larger simulation model is chosen, the increase between the time profiles will be smaller. For a smaller model we would see the opposite effect. In case of the Utsira Sand with its extremely large size, high permeability and the total injection amount of 10 Mt of CO_2 over ten years, there would be no perceptible volumetric effects. It is expected that all pressure profiles will plot over each other into a single thicker line.

Figure 9 shows the CO_2 density development for the same column of grid blocks. The upward shifting of the profiles is naturally a result of the nearly 400 kPa increase in average field/model pressure. But the main conclusion of this study is the substantial decrease in density if CO_2 moves upwards through the critical point and the normal proportional effect on the volume of the CO_2. The expansion of CO_2 will reduce its density and subsequently reduce the efficiency of the storage. From the plot the important role of the temperature is also evident. If the pressure decreases at a relative low temperature, an abrupt and much more rapid transition can be expected in the upper part of the formation. If the pressure decreases at higher temperature, the expansion will take place gradually and smoothly.

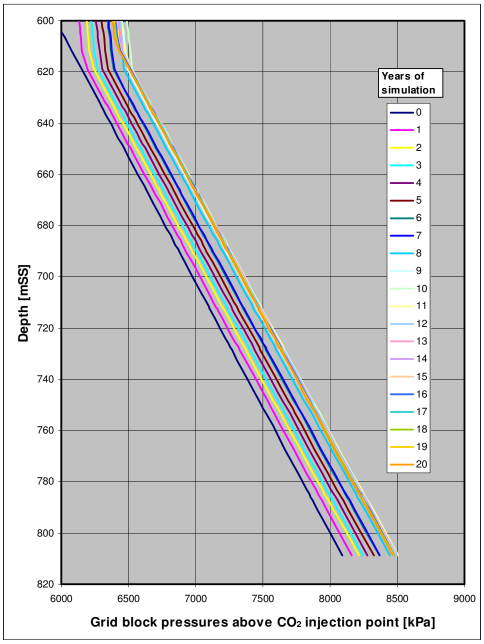


Figure 8. Vertical pressure gradient above the injection point for different times (in years).

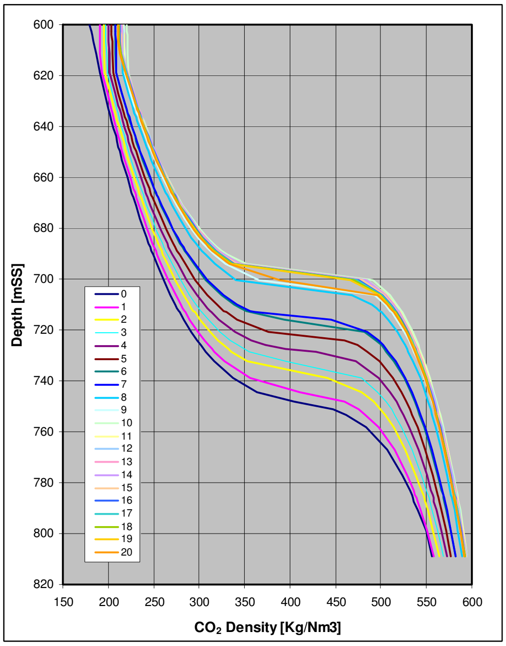


Figure 9. CO_2 density profile above the injection point for different times (in years).

Acknowledgements

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